

A New Experiment to Study Hyperon CP Violation, Charmonium, and Charm*

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Abstract

Fermilab operates the world's most intense antiproton source, now exclusively dedicated to serving the needs of the Tevatron Collider. The anticipated 2009 shutdown of the Tevatron presents the opportunity for world-leading low- and medium-energy antiproton programs. We summarize the status of the Fermilab antiproton facility and review physics topics for which a future experiment could make the world's best measurements.

1 Overview

Fermilab operates the world's highest-energy (8 GeV kinetic) and highest-intensity antiproton source. The luminosity needs of the Tevatron Collider have engendered a continuous performance-improvement program, so that the stacking rate, $\approx 2 \times 10^{11} \bar{p}/\text{hr}$, is now some five times that in E835 [1] (the last time the Antiproton Source was used for medium-energy experiments), and an order of magnitude beyond that planned [2] for the Gesellschaft für Schwerionenforschung (GSI) Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [3]. With the planned 2009 shutdown of the Tevatron, the Fermilab Antiproton Source could once again become available for medium-energy experiments.

Using the Antiproton Source, Fermilab experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [1, 4]. This precision ($\lesssim 100 \text{ keV}$) reflects the narrow energy spread of the stochastically cooled antiproton beam and the absence of Fermi motion and negligible energy loss in hydrogen cluster-jet targets. The other key advantage of $\bar{p}p$ annihilation is its ability to produce charmonium states of all quantum numbers, whereas e^+e^- machines produce primarily 1^{--} states.

Additional running in the charmonium region would be valuable for clarifying some still-elusive aspects of the charmonium system (Figure 1), including the h_c mass and width, χ_c radiative-decay angular distributions, and $\eta'_c(2S)$ full and radiative widths. It would also afford the opportunity for precision studies of a number of recently observed states in the charmonium region whose nature has not been determined: the $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$ [5]. As we will see, improved sensitivity is possible not only by virtue of longer running time, but also via higher luminosity and use of a magnetic spectrometer (in contrast to that of E760 and E835, which relied primarily on electromagnetic calorimetry to “dig” the rare charmonium signals out of the $\sim 100 \text{ mb}$ total cross section).

Antiproton annihilation has also proved valuable for hyperon studies [6]. Possibly the highest-impact issue in hyperon physics today is whether and to what extent hyperon decays violate CP symmetry. As Table 2 indicates, until 2000 the world's most sensitive search for hyperon CP violation was by PS185 at LEAR, using an antiproton flux $< 10^6 \text{ Hz}$. The orders-of-magnitude-higher rate at Fermilab can enable the world's most sensitive search and possibly find so-far elusive contributions due to new physics.

Currently the world's most sensitive hyperon experiment is HyperCP, where a surprise—the observation of apparent flavor-changing neutral currents (FCNC) in hyperon decay [7]—deserves further experimental attention.

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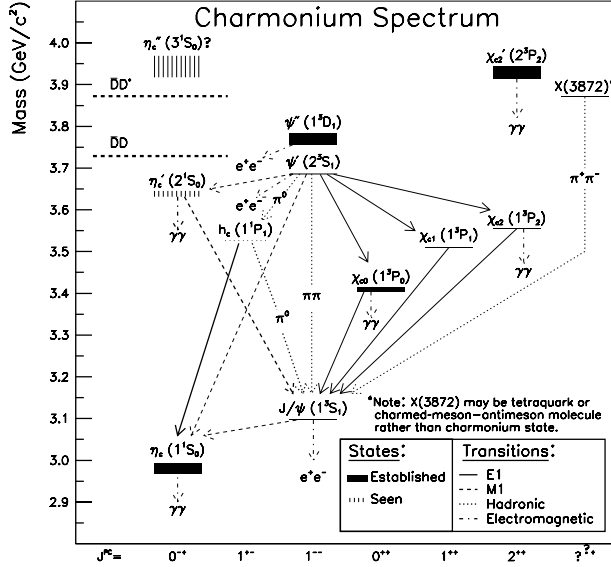


Figure 1: Spectrum of the charmonium system. Shown are masses, widths (or for those not yet measured, 90% confidence level upper limits on widths), and quantum numbers of observed charmonium states, with some of the important transitions also indicated [9, 5].

The rate of D -pair production has been estimated at about 100/s for \sqrt{s} near the $\psi(4040)$ [8]. This could lead to a sample of $\sim 10^9$ events/year produced and $\sim 10^8$ /year reconstructed, roughly an order of magnitude beyond the statistics accumulated by the B Factories so far. There is thus the potential for competitive measurements, e.g., of D^0 mixing and possible CP violation in charm decay.

Table 1 lists center-of-mass energies and lab-frame antiproton momenta for some processes of possible interest. The measurements mentioned above can be performed with a common apparatus using existing technologies. Depending on available resources, existing detector components might be recycled for these purposes; alternatively, modest expenditures for new equipment could yield improved performance. We propose to run with up to ten times the typical E835 luminosity [1] ($\mathcal{L} \lesssim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$), via increased store intensity or target density.

Further detail on our proposed experimental program may be found below and in [10] and [11].

2 Physics Examples

We next consider representative physics examples: studying the $X(3872)$, improved measurement of the

Table 1: Thresholds for some processes of interest and lab-frame \bar{p} momentum for $\bar{p}p$ fixed-target.

| Process | Threshold | |
|---|---------------------|--------------------------|
| | \sqrt{s} (GeV) | $p_{\bar{p}}$ (GeV/c) |
| $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ | 2.231 | 1.437 |
| $\bar{p}p \rightarrow \bar{\Sigma}^-\Sigma^+$ | 2.379 | 1.854 |
| $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ | 2.642 | 2.620 |
| $\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$ | 3.345 | 4.938 |
| $\bar{p}p \rightarrow \eta_c$ | 2.980 | 3.678 |
| $\bar{p}p \rightarrow \psi(3770)$ | 3.771 | 6.572 |
| $\bar{p}p \rightarrow X(3872)$ | 3.871 | 6.991 |
| $\bar{p}p \rightarrow X \text{ or } Y(3940)$ | 3.940 | 7.277 |
| $\bar{p}p \rightarrow Y(4260)$ | 4.260 | 8.685 |

parameters of the h_c , searching for hyperon CP violation, and studying a recently discovered rare hyperon-decay mode. (This list is not exhaustive; see Sec. 2.5 for additional topics.)

2.1 $X(3872)$

The best established of the new states, the $X(3872)$ was discovered [12] in 2003 by the Belle Collaboration via $B^\pm \rightarrow K^\pm X(3872)$, $X(3872) \rightarrow \pi^+\pi^- J/\psi$, and quickly confirmed by CDF [13], DØ [14], and BaBar [15]. It does not appear to fit within the charmonium spectrum [5]. The coincidence of the $X(3872)$ with $D^0\bar{D}^{*0}$ threshold suggests possible novel interpretations: an S -wave cusp [16], a tetraquark state [17], or a meson-antimeson molecule—a bound state of $D^0\bar{D}^{*0} + D^{*0}\bar{D}^0$ [18].¹ A key measurement is the precise mass difference between the X and that threshold, which should be slightly negative, in accord with the small molecular binding energy [19]:

$$0 < E_X = (m_{D^0} + m_{D^{*0}} - m_X)c^2 \ll 10 \text{ MeV}. \quad (1)$$

(A measurement of the width is also highly desirable.) Current measurements [20] give $E_X = 0.6 \pm 0.6 \text{ MeV}/c^2$, with the uncertainty dominated by that of m_X . The $\bar{p}p$ formation technique should be able to tighten the uncertainty by nearly an order of magnitude. Additional measurements, including $\mathcal{B}[X(3872) \rightarrow \pi^0\pi^0 J/\psi]$ and $\mathcal{B}[X(3872) \rightarrow \gamma\psi']$, will also contribute to quantum-number determination [21, 5].

¹The mass coincidence may be accidental, and the $X(3872)$ a $c\bar{c}$ -gluon hybrid state; however, the mass and quantum numbers make it a poor match to lattice-QCD predictions for such states [5].

The $\bar{p}p \rightarrow X(3872)$ cross section is unmeasured but estimated to be similar in magnitude to those for χ_c [22]. This estimate is supported by the observed rates and distributions of $\bar{p}p \rightarrow X(3872) + \text{anything}$ at the Tevatron [14] and of $B^\pm \rightarrow K^\pm X(3872)$ [9], which resemble those for charmonium states. Extrapolation from E760's $\chi_{c1}, \chi_{c2} \rightarrow \gamma J/\psi$ signals [23] implies $\gtrsim 4 \times 10^3$ $X(3872)$ events per nominal month (1.0×10^6 s) of running, a rate competitive even with that of the proposed SuperKEKB upgrade [24] (should that project go forward).

Given the uncertainties in the cross section and branching ratios [25], the above may well be an under- or overestimate of the $\bar{p}p$ formation and observation rates, perhaps by as much as an order of magnitude. Nevertheless, it appears that a new experiment at the Antiproton Source could obtain the world's largest clean samples of $X(3872)$, in perhaps as little as a month of running. The high statistics, event cleanliness, and unique precision available in the $\bar{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

2.2 h_c

Observing the $h_c(1^1P_1)$ charmonium state and measuring its parameters were high-priority goals of E760, E835, and their predecessor experiment, CERN R704. As a narrow state with suppressed couplings both to e^+e^- and to the states that are easily produced in e^+e^- annihilation, the h_c is a difficult state to study experimentally.

A key prediction of QCD and perturbation theory is that the charmonium spin-zero hyperfine splitting, as measured by the mass difference Δm_{hf} between the h_c and the spin-weighted average of the χ_c states, should be close to zero [26]. Current PDG-average values [9] give $\Delta m_{\text{hf}} = -0.57 \pm 0.28$ MeV, nonzero at 2σ but within the QCD expected range.

The PDG-average $m(h_c)$ value is based on claimed observations by CERN R704 (Baglin *et al.*) of $h_c \rightarrow J/\psi X$ (5 events) [27], E760 of $J/\psi \pi^0$ (59 events) [28], and E835 (13 events) and CLEO (168 ± 40 events) of $\eta_c \gamma$ [29, 31]. The PDG error on $m(h_c)$ includes a scale factor of 1.5 due to the tension among these measurements. Moreover, the two most precise (E760 and E835) are based on statistically marginal ($< 3\sigma$) signals, and the reliability of the E760 result is called into question by the negative results of the E835 $h_c \rightarrow J/\psi \pi^0$ search [29]. The R704 result is on even weaker ground: a $\bar{p}p \rightarrow h_c \rightarrow J/\psi X$ signal at the level implied by Baglin *et al.* [27] is most likely ruled out by E760 [30] as well as by E835 [29].

Thus of the four results used by the PDG, only one is clearly reliable, and the claimed precision on $m(h_c)$ is far from established. This motivates an improved experimental search. Also of interest are the width and branching ratios of the h_c , for which QCD makes clear predictions; the decay modes also bear on the question of isospin conservation in such decays.

E835's $h_c \rightarrow \eta_c \gamma \rightarrow (\gamma\gamma)\gamma$ sensitivity was limited by the $(2.8 \pm 0.9) \times 10^{-4}$ $\eta_c \rightarrow \gamma\gamma$ branching ratio, and their acceptance \times efficiency was only $\approx 3\%$ due to cuts against the substantial π^0 background [29]. With a magnetic spectrometer, likely η_c modes include $\phi\phi$, $\phi K^+ K^-$, $K^* K^*$, and $\eta' \pi^+ \pi^-$. These have branching ratios up to two orders of magnitude larger, as well as more-distinctive decay kinematics than $\gamma\gamma$, probably allowing looser cuts and thus higher efficiency. For example, the $\phi\phi \rightarrow K^+ K^- K^+ K^-$ final state has no quarks in common with the initial $\bar{p}p$ state and so should contain little background. E835 searched for $\eta_c \rightarrow \phi\phi$ but without a magnet it was barely feasible. Assessing the degree of improvement will require detailed simulation work, but at least an order of magnitude in statistics seems likely. Additional improvement will come from the higher luminosity we propose.

Provided detailed simulation studies bear out these ideas, we will soon have the opportunity to resolve this 20-year-old experimental controversy.

2.3 Hyperon CP violation

The standard model (SM) predicts only slight ($\lesssim 10^{-5}$) hyperon-decay CP asymmetries [32]–[34]. Standard-model processes dominate K and B CP asymmetries, thus it behooves us to study hyperons (and charm), in which new physics might stand out more sharply.

More than one hyperon CP asymmetry may be measurable in $\bar{p}p$ annihilation. To conserve baryon number, hyperon CP violation must be of the direct type. Accessible signals include angular-distribution differences of polarized-hyperon and antihyperon decay products [33]; partial-rate asymmetries, at possibly detectable levels, are also expected [35, 36]. To compete with previous Ξ and Λ CP studies would require $\sim 10^{33}$ luminosity. While summarizing the state of hyperon CP violation generally, we therefore emphasize in particular the $\Omega^-/\bar{\Omega}^+$ partial-rate asymmetry, for which there is no previous measurement.

By angular-momentum conservation, in the decay of a spin-1/2 hyperon to a spin-1/2 baryon plus a meson, the final state must be either S -wave or P -wave.²

²A similar argument holds for a spin-3/2 hyperon, but involving P and D waves.

Interference between the S - and P -wave decay amplitudes causes parity violation, described by Lee and Yang [37] in terms of two independent parameters α and β , proportional respectively to the real and imaginary parts of the interference term. Hyperon CP -violation signatures include differences in $|\alpha|$ or $|\beta|$ between a hyperon decay and its CP -conjugate antihyperon decay, as well as particle–antiparticle decay partial-width differences between a mode and its CP conjugate [33, 38]. Precision angular-distribution asymmetry measurement requires accurate knowledge of the relative polarizations of the initial hyperons and antihyperons.

2.3.1 Angular-distribution asymmetries

Table 2 summarizes the experimental situation. The first three experiments cited studied Λ decay only [39]–[41] setting limits on the CP -asymmetry parameter [33, 38]

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda}, \quad (2)$$

where α_Λ ($\bar{\alpha}_\Lambda$) characterizes the Λ ($\bar{\Lambda}$) decay to (anti)proton plus charged pion. If CP is a good symmetry in hyperon decay, $\alpha_\Lambda = -\bar{\alpha}_\Lambda$.

Fermilab fixed-target experiment E756 [42] and CLEO [43] used the decay of charged Ξ hyperons to produce polarized Λ 's, in whose subsequent decay the slope of the (anti)proton angular distribution in the “helicity” frame measures the product of α_Ξ and α_Λ . If CP is a good symmetry in hyperon decay this product should be identical for Ξ^- and $\bar{\Xi}^+$ events. The CP -asymmetry parameter measured is thus

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \bar{\alpha}_\Xi\bar{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda + \bar{\alpha}_\Xi\bar{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda. \quad (3)$$

Subsequent to E756, this technique was used in the “HyperCP” experiment (Fermilab E871) [44, 45], which ran during 1996–99 and has set the world's best limits on hyperon CP violation, based so far on about 5% of the recorded $(\Xi^\mp) \rightarrow (\bar{\Lambda}) \pi^\mp$ data sample. (The systematics of the full data sample is still under study.) HyperCP recorded the world's largest samples of hyperon and antihyperon decays, including 2.0×10^9 and 0.46×10^9 Ξ^- and $\bar{\Xi}^+$ events, respectively. When the analysis is complete, these should determine $A_{\Xi\Lambda}$ with a statistical uncertainty

$$\delta A = \frac{1}{2\alpha_\Xi\alpha_\Lambda} \sqrt{\frac{3}{N_{\Xi^-}} + \frac{3}{N_{\bar{\Xi}^+}}} \lesssim 2 \times 10^{-4}. \quad (4)$$

The standard model predicts [33] this asymmetry to be of order 10^{-5} . (A number of standard-model extensions, e.g. nonminimal SUSY, predict effects as

large as $\mathcal{O}(10^{-3})$ [46].) Thus any significant effect seen in HyperCP will be evidence for new sources of CP violation in the baryon sector. Such an observation could be of relevance to the mysterious mechanism that gave rise to the cosmic baryon asymmetry.

HyperCP has also set the world's first limit on CP violation in $(\bar{\Omega})^\mp$ decay, using a sample of 5.46 (1.89) million $\Omega^- \rightarrow \Lambda K^-$ ($\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$) events [47]. Here, as shown by HyperCP [48, 49], parity is only slightly violated: $\alpha = (1.75 \pm 0.24) \times 10^{-2}$ [9]. Hence the measured magnitude and uncertainty of the asymmetry parameter $A_{\Omega\Lambda}$ (inversely proportional to α as in Eq. 4) are rather large: $[-0.4 \pm 9.1 \text{ (stat)} \pm 8.5 \text{ (syst)}] \times 10^{-2}$ [47]. This asymmetry is predicted to be $\leq 4 \times 10^{-5}$ in the standard model but can be as large as 8×10^{-3} if new physics contributes [36].

2.3.2 Partial-rate asymmetries

While CPT symmetry requires identical lifetimes for particle and antiparticle, partial-rate asymmetries violate only CP . For most hyperon decays, these are expected to be undetectably small [34]. However, for the decays $\Omega^- \rightarrow \Lambda K^-$ and $\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$, the particle/antiparticle partial-rate asymmetries could be as large as 2×10^{-5} in the standard model and one to two orders of magnitude larger if non-SM contributions dominate [35, 36]. The quantities to be measured are

$$\begin{aligned} \Delta_{\Lambda K} &\equiv \frac{\Gamma(\Omega^- \rightarrow \Lambda K^-) - \Gamma(\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+)}{\Gamma(\Omega^- \rightarrow \Lambda K^-) + \Gamma(\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+)} \\ &\approx \frac{1}{2\bar{\Gamma}} (\Gamma - \bar{\Gamma}) \approx 0.5 (1 - N/\bar{N}) \end{aligned}$$

(and similarly for $\Delta_{\Xi\pi}$), where in the last step we have assumed nearly equal numbers (N) of Ω and (\bar{N}) of $\bar{\Omega}$ events, as would be the case in $\bar{p}p$ annihilation. Sensitivity at the 10^{-4} level then requires $\mathcal{O}(10^7)$ reconstructed events. Measuring such a small branching-ratio difference reliably will require the clean exclusive $\bar{\Omega}^+ \Omega^-$ event sample produced less than a π^0 mass above threshold, or $4.938 < p_{\bar{p}} < 5.437 \text{ GeV}/c$.

The inclusive hyperon-production cross section at $5.4 \text{ GeV}/c$ is $\approx 1 \text{ mb}$ [10, 11] (Fig. 2). At $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ this amounts to some 2×10^5 hyperon events produced per second, or 2×10^{12} per year. (Experience suggests that a data-acquisition system that can cope with such a high event rate is both feasible and reasonable in cost. For example, the $\bar{p}p$ interaction rate is comparable to that in BTeV, yet the charged-particle multiplicity per event is only $\approx 1/10$ as large.)

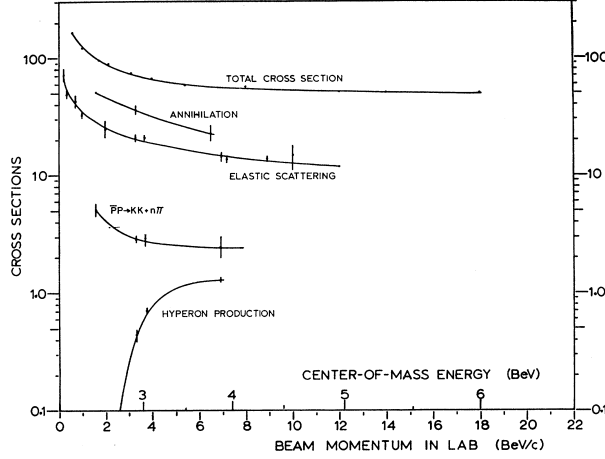


Figure 2: Cross sections (in mb) for various $\bar{p}p$ processes vs. momentum and \sqrt{s} (from [50]).

To estimate the exclusive $\bar{p}p \rightarrow \bar{\Omega}\Omega$ cross section requires some extrapolation, since it has yet to be measured. The cross section for $\bar{\Xi}^+\Xi^-$ somewhat above threshold ($p_{\bar{p}} \approx 3.5 \text{ GeV}/c$) is $\approx 2 \mu\text{b}$ [6, 51, 52], or about 1/30 of the corresponding cross section for $\bar{\Lambda}\Lambda$. Thus the $\approx 65 \mu\text{b}$ cross section measured for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at $p_{\bar{p}} = 1.642 \text{ GeV}/c$ at LEAR [53] implies $\sigma(\bar{p}p \rightarrow \bar{\Omega}\Omega) \sim 60 \text{ nb}$ at $5.4 \text{ GeV}/c$.

For purposes of discussion we take this as the exclusive production cross section.³ At $2.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ luminosity, some 1.2×10^8 $\bar{\Omega}\Omega$ events are then produced in a nominal 1-year run ($1.0 \times 10^7 \text{ s}$). Assuming 50% acceptance times efficiency (comparable to that for χ_c events in E760), we estimate $\langle N_{\Xi\pi} \rangle = 1.4 \times 10^7$ events each in $\Omega^- \rightarrow \Xi^0\pi^-$ and $\bar{\Omega}^+ \rightarrow \bar{\Xi}^0\pi^+$, and $\langle N_{\Lambda K} \rangle = 4.1 \times 10^7$ events each in $\Omega^- \rightarrow \Lambda K^-$ and $\bar{\Omega}^+ \rightarrow \bar{\Lambda}K^+$, implying the partial-rate-asymmetry statistical sensitivities

$$\delta\Delta_{\Xi\pi} \approx \frac{0.5}{\sqrt{N_{\Xi\pi}}} \approx 1.3 \times 10^{-4},$$

$$\delta\Delta_{\Lambda K} \approx \frac{0.5}{\sqrt{N_{\Lambda K}}} \approx 7.8 \times 10^{-5}.$$

Tandean and Valencia [35] have estimated $\Delta_{\Xi\pi} \approx 2 \times 10^{-5}$ in the standard model but possibly an order of magnitude larger with new-physics contributions. Tandean [36] has estimated $\Delta_{\Lambda K}$ to be $\leq 1 \times 10^{-5}$ in the standard model but possibly as large as 1×10^{-3} if new physics contributes. (The large sensitivity of $\Delta_{\Lambda K}$ to new physics in this analysis arises from chromomagnetic penguin operators and final-state inter-

actions via $\Omega \rightarrow \Xi\pi \rightarrow \Lambda K$ [36].⁴) It is worth noting that these potentially large asymmetries arise from parity-conserving interactions and hence are limited by constraints from ϵ_K [35, 36]; they are independent of A_Λ and A_Ξ , which arise from the interference of parity-violating and parity-conserving processes [54].

Experimental sensitivities will include systematic components whose estimation will require careful and detailed simulation studies yet to be done. Nevertheless, the potential power of the technique is apparent: the experiment discussed here may be capable of observing the effects of new physics in Omega CP violation via partial-rate asymmetries, and it will represent a substantial improvement over current sensitivity to Omega angular-distribution asymmetries.

2.4 Study of FCNC hyperon decays

Behind its charged-particle spectrometer, HyperCP had muon detectors for rare-decay studies [45, 7]. Using them HyperCP has observed [7] the rarest hyperon decay ever, $\Sigma^+ \rightarrow p\mu^+\mu^-$. Surprisingly (Fig. 3), the 3 observed events are consistent with a two-body decay, $\Sigma^+ \rightarrow pX^0$, $X^0 \rightarrow \mu^+\mu^-$, with X^0 mass $m_{X^0} = 214.3 \pm 0.5 \text{ MeV}/c^2$. This interpretation is of course not definitive, with the confidence level for the form-factor decay spectrum of Fig. 3d estimated at 0.8%. The measured branching ratio is $[3.1 \pm 2.4 (\text{stat}) \pm 1.5 (\text{syst})] \times 10^{-8}$ assuming two-body, or $[8.6_{-5.4}^{+6.6} (\text{stat}) \pm 5.5 (\text{syst})] \times 10^{-8}$ assuming three-body Σ^+ decay.

The X^0 , if real, cannot be an ordinary hadron. A light, scalar or vector particle coupling to hadrons and muon pairs at the required level is ruled out by its non-observation in kaon decays [56]–[58]. However, there are at least two possible supersymmetric interpretations. It could be a pseudoscalar “sgoldstino” [56]–[58] or the light pseudoscalar Higgs boson (A_1^0) in the next-to-minimal supersymmetric standard model [59].

Searching for this decay with exclusive $\bar{\Sigma}^-\Sigma^+$ events just above threshold would require \bar{p} momentum (see Table 1) well below that previously achieved by deceleration in the Antiproton Accumulator, as well as very high luminosity to access the $\mathcal{O}(10^{-8})$ branching ratio. An experimentally less challenging but equally interesting objective is the corresponding FCNC decay of the Ω^- , with $\mathcal{O}(10^{-6})$ predicted branching ratio [56] if the X^0 is real.⁵ (The larger branching ratio reflects the additional phase space

⁴Large final-state interactions should also affect $\Delta_{\Xi\pi}$ but were not included in that prediction [35, 54].

⁵The standard-model prediction is [60] $\mathcal{B}(\Omega^- \rightarrow \Xi^-\mu^+\mu^-) = 6.6 \times 10^{-8}$.

available compared to that in $\Sigma^+ \rightarrow p\mu^+\mu^-$.) As above, assuming 2×10^{32} luminosity and 50% acceptance times efficiency, 120 or 44 events are predicted in the two cases (pseudoscalar or axial-vector X^0) that appear to be viable [56, 57]:

$$\begin{aligned}\mathcal{B}(\Omega^- \rightarrow \Xi^- X_P \rightarrow \Xi^- \mu^+ \mu^-) &= \\ & (2.0^{+1.6}_{-1.2} \pm 1.0) \times 10^{-6}, \\ \mathcal{B}(\Omega^- \rightarrow \Xi^- X_A \rightarrow \Xi^- \mu^+ \mu^-) &= \\ & (0.73^{+0.56}_{-0.45} \pm 0.35) \times 10^{-6}.\end{aligned}$$

Given the large inclusive hyperon rates at $\sqrt{s} \approx 3.5$ GeV, sufficient sensitivity might also be available at that setting to confirm the HyperCP $\Sigma^+ \rightarrow p\mu^+\mu^-$ results. Alternatively, it is possible that a dedicated run just above $\bar{\Sigma}^-\Sigma^+$ threshold may have competitive sensitivity; evaluating this will require a detailed simulation study.

2.5 Additional physics

Besides the $X(3872)$, the experiment would be competitive for the charmonium and related states mentioned above. The large hyperon samples could enable precise measurement of hyperon semileptonic and other rare decays. The APEX experiment [61] vacuum tank and pumping system could be re-installed, enabling substantially increased sensitivity for \bar{p} lifetime and decay modes. There is interest in decelerating further (e.g., at the ends of stores) for trapped-antiproton and antihydrogen experiments [62, 63]. This capability could make Fermilab the premier facility for such research. The \bar{p} intensity available at Fermilab could enable studies not feasible at the AD, such as a measurement of the gravitational force on antimatter [63]. A complementary approach is the study of antihydrogen atoms in flight [64], which may overcome some of the difficulties encountered in the trapping experiments.

3 A New Experiment

We see two approaches to implementing low-cost apparatus to perform the measurements here described [10]: one based on existing equipment from E835, and the other on the DØ superconducting solenoid (available once the Tevatron Collider program ends). Should sufficient resources be available, a new spectrometer, free of constraints from existing apparatus, may give better performance than either of these. The possibility of building a new storage ring has also been mentioned. We hope to study these options in detail in the coming months.

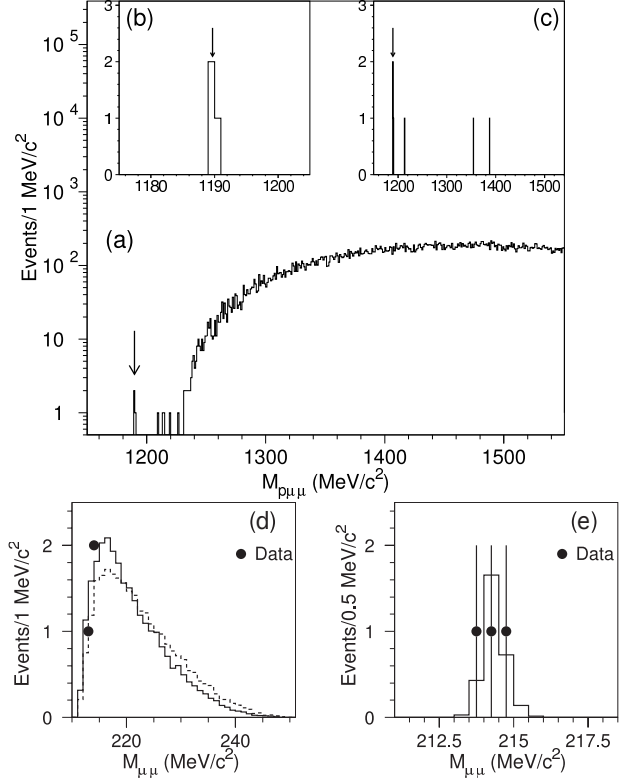


Figure 3: Mass spectra for candidate single-vertex $p\mu^+\mu^-$ events in HyperCP positive-beam data sample: (a) wide mass range (semilog scale); (b) narrow range around Σ^+ mass; (c) after application of additional cuts as described in Ref. [7] (arrows indicate mass of Σ^+); dimuon mass spectrum of the candidate events compared with Monte Carlo spectrum assuming (d) standard-model virtual-photon form factor (solid) or isotropic decay (dashed), or (e) decay via a narrow resonance X^0 .

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Table 2: Summary of experimental limits on CP violation in hyperon decay; the hyperons studied are indicated by *, † , and ‡ .

| Exp't | Facility | Year | Ref. | Modes | $^*A_\Lambda / ^\dagger A_{\Xi\Lambda} / ^\ddagger A_{\Omega\Lambda}$ |
|---------|----------|------|------|--|---|
| R608 | ISR | 1985 | [39] | $pp \rightarrow \Lambda X, pp \rightarrow \bar{\Lambda} X$ | $-0.02 \pm 0.14^*$ |
| DM2 | Orsay | 1988 | [40] | $e^+e^- \rightarrow J/\psi \rightarrow \Lambda \bar{\Lambda}$ | $0.01 \pm 0.10^*$ |
| PS185 | LEAR | 1997 | [41] | $\bar{p}p \rightarrow \bar{\Lambda} \Lambda$ | $0.006 \pm 0.015^*$ |
| CLEO | CESR | 2000 | [43] | $e^+e^- \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $e^+e^- \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$ | $-0.057 \pm 0.064 \pm 0.039^\dagger$ |
| E756 | FNAL | 2000 | [42] | $pN \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $pN \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$ | $0.012 \pm 0.014^\dagger$ |
| HyperCP | FNAL | 2004 | [44] | $pN \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $pN \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$ | $(0.0 \pm 6.7) \times 10^{-4}{}^\dagger, {}^\S$ |
| HyperCP | FNAL | 2006 | [47] | $pN \rightarrow \Omega^- X, \Omega^- \rightarrow \Lambda K^-$, $pN \rightarrow \bar{\Omega}^+ X, \bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$ | $-0.004 \pm 0.12^\ddagger$ |

§ Based on $\approx 5\%$ of the HyperCP data sample; analysis of the full sample is still in progress.